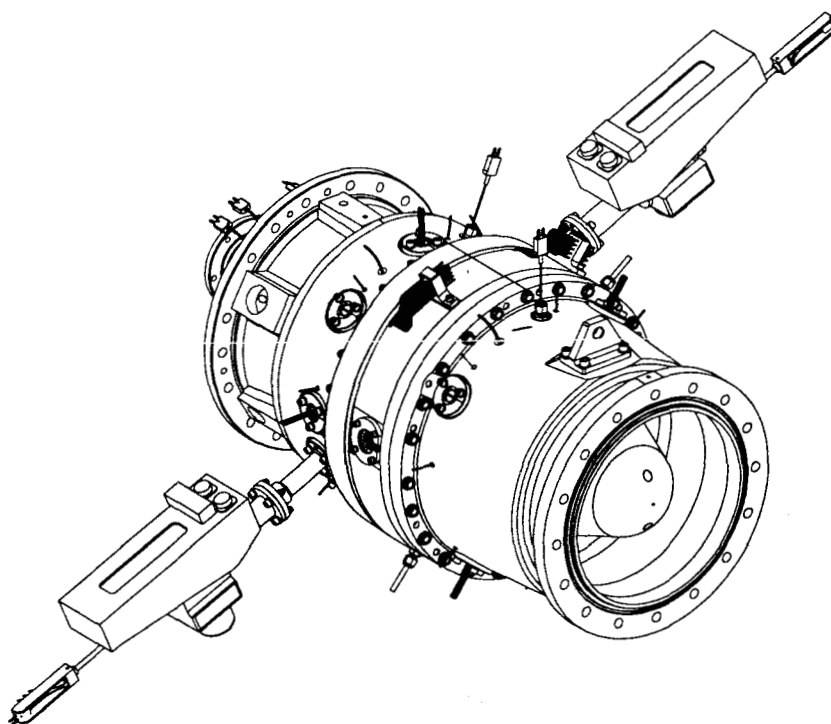


MECHANICAL DESIGN OF A PERFORMANCE TEST RIG FOR THE TURBINE AIR-FLOW TASK (TAFT)

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ABSTRACT

To support development of the Boeing-Rocketdyne RS84 rocket engine, a full-flow, reaction turbine geometry was integrated into the NASA-MSFC turbine air-flow test facility. A mechanical design was generated which minimized the amount of new hardware while incorporating all test and instrumentation requirements. This paper provides details of the mechanical design for this Turbine Air-Flow Task (TAFT) test rig. The mechanical design process utilized for this task included the following basic stages:

- Conceptual Design
- Preliminary Design
- Detailed Design

- Baseline of Design (including Configuration Control and Drawing Revision)
- Fabrication
- Assembly

During the design process, many lessons were learned that should benefit future test rig design projects. Of primary importance are well-defined requirements early in the design process, a thorough detailed design package, and effective communication with both the customer and the fabrication contractors.

INTRODUCTION

Due to the aggressive development schedule for the RS84 engine, the time allowed for design, fabrication, assembly and test of this turbine performance test rig was limited to

about 18 months. To complete the detailed design within the allotted time, the 3D Computer-Aided Design (CAD) software package, Unigraphics, and the electronic database, iMAN, were used throughout all stages of design.

Each of these stages and their lessons learned are discussed in detail. Also, included are lessons learned during the fabrication, assembly and testing phases.

RESULTS AND DISCUSSION

TASK INITIATION

To support engine development for the Space Launch Initiative (SLI) Program (later known as Next Generation Launch Technology- NGLT), a Task Agreement was approved for design and performance testing by MSFC of a full-flow, reaction turbine, similar to the design to be used for the RS83 rocket engine. The test rig was to provide steady and unsteady pressure data necessary to validate the CORSAIR computational fluid dynamics (CFD) code. The rig would also help characterize the turbine blade loading conditions. The RS83 engine program was subsequently cancelled and replaced by the RS84 engine program. Fortunately, the RS84 turbomachinery also utilized similar full-flow, reaction turbines.

Before the design of the test rig could commence, interface meetings between the Task Manager (Robert Williams, NASA/MSFC, TD64) and the customer (Boeing-Rocketdyne) were necessary to define the test requirements and schedule. Due to the aggressive engine design schedule, only about 18 months were available for completion of this task in order to provide useful performance data to support the RS83 (now RS84) Preliminary Design Review (PDR). Therefore, a decision was made to use the existing Integrated Powerhead Demonstration (IPD) liquid oxygen turbopump full-flow turbine design for this test program.

For this task, the minimum success criteria was to provide steady and unsteady performance data for only one full-flow, reaction turbine configuration. However, the TAFT team's plan was to test a total of four configurations. This required the mechanical design of two different nozzle vane assemblies and provisions for testing each at two different nozzle-to-rotor axial distances (25% and 40% of nozzle vane midline axial chord length).

The design team was formed in September of 2001. The Design Kickoff Meeting was held on 11 September 2001. In addition to representatives from mechanical design (TD62) and CFD (TD64) groups, the design team included stress, structural dynamics, rotor-dynamics and materials analysts. From the start, the customer was also considered an integral part of the team. During the design

phase, design status meetings were held weekly with the customer.

CONCEPTUAL DESIGN

Prior to receiving the IPD turbine models from the customer, the mechanical design team thoroughly studied the air-flow test facility documentation. One member of the team prepared a drawing tree for the existing test rig assemblies and organized a complete set of drawings.

The conceptual design layout process began with the modeling of what became known as the "deoutfitted configuration." This configuration defined the interfaces to which the TAFT test article had to adapt. It included the bearing / turbine discharge housing, the rotating shaft and the rotating turbine drive flange. The axial position of the inlet flange relative to the discharge housing flange interface was also defined. This layout file was to serve as the interface control for most of the TAFT component models.

The IPD turbine operating conditions were then scaled to air-flow conditions. To minimize the flow-path scaling factor, a turbine test rig operating speed was desired to be as close to the allowable test facility speed limit of 12,500 RPM as practical. Rotordynamic analysts determined that a maximum speed limit of 11,348 RPM, which included an 18% margin on the first critical mode, should be the design limit. With the selected speed of 11,348 RPM and inlet conditions of 70 psia and 100 °F missile grade air, analysis indicated that a scaling factor of 1.42 needed to be applied to the IPD turbine geometry.

An envelope representing the IPD turbine blade flowpath (scaled by a factor of 1.42) was incorporated onto the layout. It was immediately apparent that, due to the large TAFT turbine diameters, none of the existing inlet housings, including the rotating traverse instrumentation ring assemblies, could be used for the TAFT configuration. At this time, the TAFT team made the decision to forego a rotating traverse ring and use "stationary" pressure and temperature rakes.

In late September 2001, the customer provided 3D STEP format models of the IPD turbine rotor blade and nozzle vane geometries to MSFC. They also provided the desired midline axial spacing values between the turbine nozzle vane trailing edge and the turbine rotor blade leading edge. These geometries were incorporated into the conceptual design layout. The rotor blade was positioned axially to minimize the distance from the turbine end roller bearing to the cantilevered turbine rotor center-of-mass.

Wire-frame sketches were then used to define the contour of the flowpath from the inlet flange to the discharge passage in the existing discharge housing. The axial distance between the turbine rotor blade trailing edge and

the discharge housing was limited. Both customer and MSFC CFD engineers were asked to define the required minimum distance from the turbine rotor to the downstream instrumentation rake plane. They also indicated that the turbine discharge passage to discharge housing passage transition was acceptable.

The most critical TAFT design issue was selection of the configuration for the turbine rotor assembly. This issue needed to be addressed before a preferred conceptual design could be selected. The simplest design of a one-piece turbine blisk with integrally machined blades and outer shroud was investigated first. The IPD turbine rotor was fabricated in this manner, and the larger scale TAFT configuration would only improve its machinability. However, the requirement for mounting of on-blade pressure sensors forced the design team to take another approach. While the pressure sensors could possibly be installed on a one-piece rotor, provisions for routing the sensor wires to the slip ring assembly interface located inside the shaft would have been excessively complicated. In addition, the turbine rotor was too large for the sensor vendor's calibration chamber.

The decision was made to use individual turbine blade inserts for the rotor assembly. The primary advantage of this concept, other than allowing for the pressure sensor calibration, was that if a machining error occurred on a blade, a replacement could be manufactured without potentially scrapping the entire rotor. Another advantage to the schedule was that the proof spin test could be performed in parallel with the assembly and calibration of the instrumented turbine blade inserts. These advantages outweighed the added complexity of the blade insert attachment.

Methods for attaching the individual turbine blades to the rotor were then investigated. The initial design involved axially clamping the turbine blades to the rotor. However, due to the weight of the blade inserts (over 1 pound), the 20,000 g centrifugal loading resulted in excessive stresses and deflections at the attachment interface. In addition, any offset between the attachment centerline and the blade center of mass would tend to load the two clamping lobes unevenly and increase the stresses and deflections even more.

The fir-tree attachment was investigated next. Literature on this attachment method, including several existing turbine blade designs, was studied to ensure that it would be feasible for the TAFT configuration. Also, a simplified 3D CAD model was generated which incorporated a three-lobed fir-tree-like design onto the TAFT blade geometry. The Unigraphics' built-in finite element analysis software, Scenario for Structures, was then used to perform a medium-fidelity stress analysis on the model. When applying only the rotational loading condition of 12,500 RPM, the results were promising. However, it

became easily apparent that the fir-tree radial centerline needed to pass through the blade center-of-mass as accurately as practical.

An experienced precision fir-tree designer / manufacturer was then contacted to discuss the TAFT requirements. The primary subjects discussed were the following:

- Geometry and dimensioning
- Appropriate fabrication tolerances
- Fabrication methods {Electro-discharge machining (EDM) versus grinding}
- Inspection requirements

The lessons learned from these discussions were then incorporated into the TAFT conceptual design.

The final design issue investigated for the conceptual design of the rotor was the method of attaching the shroud to the turbine blades. The initial idea was to install a solid ring into grooves cut into the outer periphery of the blade inserts. As the rotor came up to speed, the blade inserts would expand radially against the shroud ring. Radial springs were also incorporated to initially preload the blade inserts against this outer shroud.

However, the concern that the shroud might become loose during operation led the design team toward an integrally machined shroud concept. The primary concern with this concept was the excessive deflections in the overhung shroud. Also, the blade geometry tended to twist about its radial axis, further increasing the deflections as well as affecting the flow path through the turbine.

A design team brainstorming session was held to address these issues. While the blade twisting tended to open the gap between adjacent blades with smooth shrouds, it was noted that an interlocking shroud could potentially limit the amount of blade twisting. A Z-shroud concept was then incorporated into the conceptual design, apparent in Figure 1.



Figure 1. Turbine Blade Insert Model

While no formal Conceptual Design Review (CoDR) was held at this time, a baseline conceptual design was selected. Due to the longer lead-time required for

fabrication, assembly and Kulite pressure transducer calibration of the TAFT rotor, the remainder of the design phase was performed in two stages. The rotor assembly detailed design was completed first, followed by the detailed design of the remainder of the test rig components and assemblies.

ROTOR ASSEMBLY PRELIMINARY DESIGN

Mechanical design requirements were established immediately. Yield and ultimate strength safety factors of 3 and 4, respectively, for the rotor components were set for the rotor assembly. A fatigue life requirement of 10^7 cycles was also specified. In addition to this, positive safety margins on all components at all planned operating speeds must be maintained.

To begin the preliminary design phase, a drawing tree was prepared to document all the hardware to be designed for TAFT. This drawing tree also specified the design engineer responsible for a given component.

The baseline material was then selected for each of these components. Due to its high strength and excellent corrosion resistance, 15-5 PH (15% Cr-5% Ni) stainless steel was selected for the primary rotor components. 15-5 PH is a martensitic precipitation hardenable stainless steel that is generally similar to 17-4 PH in composition and properties. However, 15-5 PH is chemically balanced to eliminate all but trace amounts of delta ferrite, thus providing superior transverse toughness and ductility plus a higher degree of forgeability. Since conditions below H1000 are not as resistance to stress corrosion cracking and since the mechanical properties decrease as the heat treatment temperature is increased, the age-hardened condition H1025 was selected.

The 3D Rotor Assembly model, shown in Figure 2, generated to support the conceptual design, was of sufficient fidelity to support the preliminary design analyses. The turbine blade and disk models were provided to the stress and structural dynamics analysts. Mass properties were also generated to support a rotor-dynamic analysis.

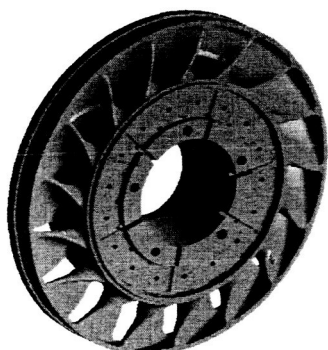


Figure 2. Rotor Assembly Model

For the detailed design of each component, individual modeling files were generated, most with parametric links to the appropriate wire-frame sketch in the master layout file. These wire-frame sketches were then used to generate the 3D component models, in most cases by revolving the sketches about a common centerline. In this way, changes to the master layout would automatically update the component models. Design features, such as hole patterns and instrumentation passages, were then added to complete the component models.

The on-blade unsteady pressure sensor selected for use with TAFT was identical to the sensor selected for a parallel MSFC test rig design, the Turbine Performance Optimization (TPO) test program. These Kulite sensors measured the unsteady data required. Initially, thirty on-blade sensor locations were specified for the TAFT program. The solid model, shown in Figure 1, for the turbine blade insert, which had basically been completed during the conceptual design phase, was linked to six files to be used for the instrumented blade models. Each of these linked solids was then modified to incorporate five dynamic pressure sensors. Only two of the six instrumented blade models were completed in time to support the TAFT PDR.

Once the 3D models were complete, the component drawings were begun. After first setting up each drawing sheet with a common drawing border, the basic views required for detailing each part were generated using the drafting application of the Unigraphics software. Each drawing view was formatted automatically, based on user inputs. This software feature greatly accelerated the part layout process. In addition, when changes were made to the model, the drawing views would be updated automatically, due to model and drawing file links in the electronic database.

Notes were then added to each drawing (as applicable) to document the following:

- Applicable Geometric Dimensioning and Tolerancing (GD&T) Specification
- Material Specifications
- Material Inspection Requirements
- Heat Treatments
- Protective Finishes
- General Surface Finish and Edge Break Requirements
- Other Special Processes

The PDR for the TAFT Rotor Assembly was held on 29 November 2001. The following documents were available for review:

- Design Layout and Functional Description
- List of Parts with Materials
- Basic Assembly Steps

- Instrumentation
 - Type
 - Location
- Assembly and Detailed Drawings
- Preliminary Stress and Structural Dynamics Reports

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ROTOR ASSEMBLY

DETAILED DESIGN

The PDR did not result in any significant design changes for the rotor assembly. Over the next five weeks, work continued on the detailed drawings for the rotor components and their assembly. The four remaining instrumented turbine blade models were also completed. In addition, the MSFC rapid prototype facility was utilized to produce stereo-lithography models of the turbine blade insert.

The Critical Design Review (CDR) for the TAFT Rotor Assembly was held on 10 January 2002. The drawing package defining the baseline configuration was basically 100% complete at that time. However, as a result of the CDR, several design changes were required.

The CDR action items that affected the mechanical design included the following:

- Excessive stress at the attachment bolt locations for the turbine rotor
- Excessive stress in the radial preload springs for the blade inserts
- Undesirable clearance at one of the two shaft pilots for the drive flange
- Requirement for ten additional on-blade pressure sensors

Each of these issues had to be addressed in a timely manner to support the Final Design Review (FDR) on 31 January 2002. In addition, the balancing assembly and tooling drawings were also completed. To simplify the review process, the FDR design presentation thoroughly documented the drawing changes made since the CDR.

ROTOR ASSEMBLY

BASELINE OF DESIGN

Waivers were required on four rotor assembly components:

- Turbine blade due to the bearing stress on fir-tree lobe
- Turbine rotor due to tangential stress adjacent to D-head bolt hole
- Drive flange due to first principle stress
- Preload clamp due to stress in spring section

After addressing the FDR action items, a final thorough drawing check was performed. A drawing package was then prepared for signature and TD62 baseline. Finally,

the appropriate design files were locked in the electronic database, iMAN.

A request for quotes along with the complete drawing package was sent out for bids.

REMAINDER OF TEST RIG

PRELIMINARY DESIGN

With the exception of the rotor assembly, the most critical components of the TAFT test rig were the turbine nozzle assemblies. The customer provided two different vane geometries: a 13-vane count configuration, shown in Figure 3. (identical to the IPD geometry) and a 22-vane count configuration.

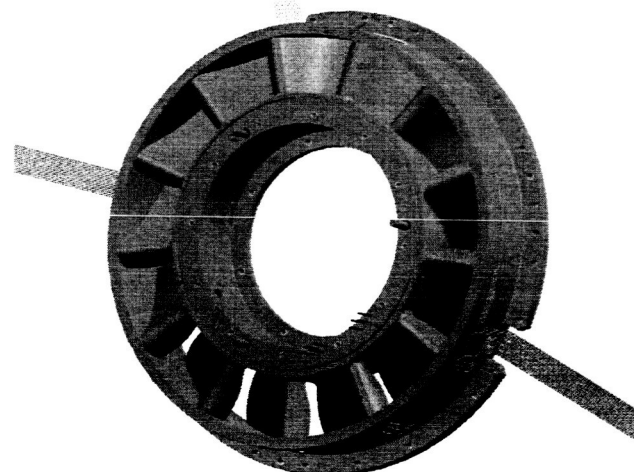


Figure 3. Nozzle Assembly Model, 13-Vane Configuration

To enhance the manufacturability of the nozzle assemblies, the vanes were machined integrally with the turbine vane hub. An outer shroud was then brazed onto the outer surfaces of the vanes.

To achieve the 25% and 40% nozzle-to-rotor axial spacing requirements, spacers were used between the nozzle assemblies and the turbine discharge housing. Since the slip ring assembly would move with the nozzle assemblies, appropriately sized spacers were also required between the slip ring assembly and the shaft. Finally, an insert was used with the nozzle assemblies to accommodate the various gaps between the nozzle assemblies and the rotor assembly at the internal flow-path contour.

In addition to the safety factors as specified for the rotor assembly, the TAFT housings had to be designed for turbine blade containment.

The test rig PDR was held on 4 April 2002.

REMAINDER OF TEST RIG

DETAILED DESIGN

Like the rotor assembly, the TAFT rig PDR did not result in any significant design changes. Over the next three weeks, work continued on the detailed drawings for the test rig components and their assembly.

The Critical Design Review (CDR) for the TAFT Rig Assembly was held on 25 April 2002. The drawing package defining the baseline configuration was basically 100% complete at that time. However, as a result of the CDR, several minor actions were issued.

The CDR action items that affected the mechanical design included the following:

- Add to plating of the drive flange inner diameter to achieve an interference fit
- Investigate capability to index rotor position with the housing top dead center
- Investigate adding cooling vent for cavity under inlet nose cone
- Determine operating clearances for critical turbine locations (rotor outer diameter and blade land hubs)
- Verify that sharp edges are removed from wiring and tubing passages

Each of these issues had to be addressed in a timely manner to support the Final Design Review (FDR) on 9 May 2002. To simplify the review process, the FDR design presentation thoroughly documented the drawing changes made since the CDR.

REMAINDER OF TEST RIG

BASELINE OF DESIGN

After addressing the FDR action items, a final thorough drawing check was performed. A drawing package was then prepared for signature and TD62 baseline. Finally, the appropriate design files were locked in the electronic database.

FABRICATION

As a result of the MSFC proposal evaluation process, two different vendors were selected for the manufacturing of the TAFT test rig- Allied Aerospace and Florida Turbine Technologies (FTT).

Allied Aerospace was selected for the machining, instrumenting, assembling and balancing of the rotor. Due to the long lead time of calibrating the rotor blade Kulite pressure transducers, fabrication of the rotor assembly was started four months before the other test rig components.

FTT was responsible for the 13-vane and 22-vane stator assemblies, all test rig housings and components, instrumentation temperature and pressure rakes, and final assembly delivery of the first test article configuration to MSFC. Both standard and state-of-the art machining operations were utilized during component fabrication including Electro-Discharge Machining (EDM). EDM machining was used on the complex instrumentation passages through the test article and on the very small static pressure ports. Five axis milling of the turbine blades and stator blisk was accomplished by machining directly from the component 3D CAD model. Standard milling techniques and lathe operations were used on some of the less complex components.

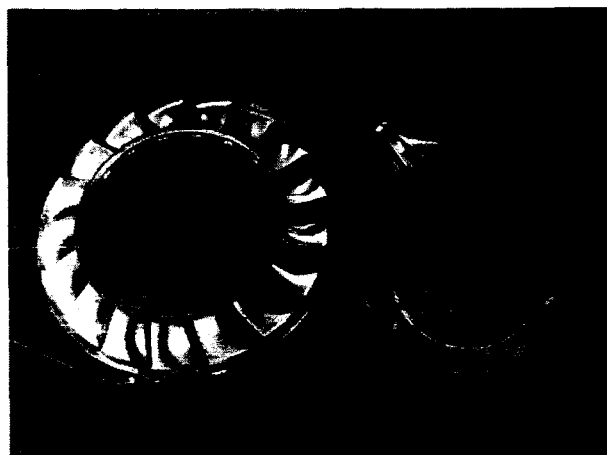


Figure 4. Rotor and Instrumented Blades

Some design changes were made by FTT with concurrence by MSFC, during the assembly of the TAFT test rig. Because of the difficulty in brazing the tubulations for static pressure measurements, the tubulations were bonded to the test article with epoxy resins instead. This proved to be both cost and schedule effective. FTT also supported the installation and check-out of the test article into the MSFC turbine airflow test facility.

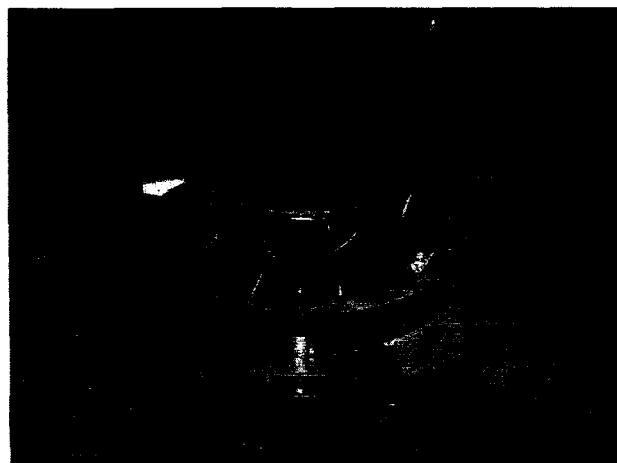


Figure 5. 13-Vane Stator in Manufacturing

ASSEMBLY

The initial assembly of the turbine test rig was performed at Florida Turbine Technologies. The test rig was then incorporated into the North Test Facility at MSFC. After the appropriate number of tests were conducted, the test rig was pulled. The test engineers and technicians would then reconfigured the test rig for the next planned configuration. This process was completed until all four TAFT configurations were tested.

Special care was taken in removing and adding components so that instrumentation wiring damage could be prevented. This process was completed until all four TAFT configurations were tested.

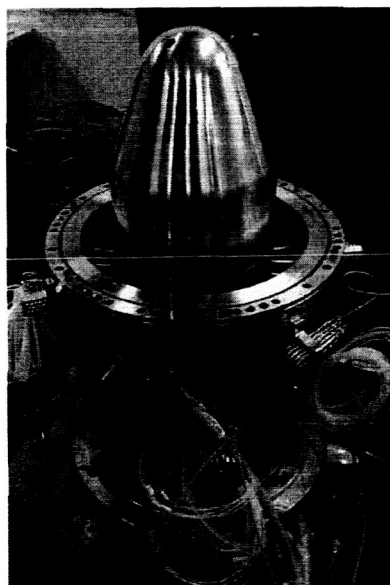


Figure 6. TAFT Test Rig Assembly at MSFC

LESSONS LEARNED

A list of lessons learned has been compiled as a benefit to future mechanical design projects.

During the design phase:

- Design requirements should be specified and documented as early in the design process as possible
- Ensure that part datum features are properly selected
- Meet with vendors to discuss their recommendations for design improvements
- Performing thorough peer reviews of detailed designs should be mandatory
 - Review design for functionality and producibility
 - Insure that all drawing requirements are specified and clearly legible
 - Insure consistent format, notes, GD&T and other requirements are used throughout the design
- All requirements (no matter how small) should be documented in the fabrication package presented to prospective vendors (i.e., be thorough)

- At beginning of task, document what design deliverables are required for each design review
- Take advantage of previous lessons learned from design of similar hardware

During the fabrication phase:

- Stress that vendors should always contact MSFC with any fabrication questions (no matter how apparently insignificant)
- Ensure that part datum features are followed throughout fabrication (especially for critical items, such as turbine blades)
- Thoroughly review vendor's fabrication and inspection plans (prior to fabrication)
- Meet with selected vendor(s) to discuss design details and recommendations for design improvements
- Schedule frequent meetings with vendor(s) to address overall status and future plans, particularly for the critical path hardware
- When evaluating vendor proposals, ensure vendor has addressed minute details that could potentially affect the cost and schedule
 - Material availability and cost
 - Critical tolerance requirements
 - Complexity of instrumentation routing

During the testing phase:

- Vacuum spin tare is especially important as the integrity of the RTV may affect validity of on-blade pressure measurements
- Boroscope holes are desirable in test rig
- Thermal flowpath liners should be designed to increase temperature measurement accuracy
- Static taps for determination of turbine reaction should be mandatory
- Should have included dynamic pressure transducers on turbine shroud as well as airfoils since unsteady forces are of interest

While most of the above seem obvious, had such a list been prepared and followed from the start of the program, more efficient design, fabrication, and test processes might have resulted.

SUMMARY AND CONCLUSIONS

The mechanical design team met all of the technical and schedule challenges which the TAFT project requirements presented. Utilizing state-of-the-art CAD tools, a detailed design package was generated in a short amount of time. Four full-flow reaction turbine configurations were successfully designed, fabricated and tested. The lessons learned from the TAFT project should greatly benefit the design of future NASA/MSFC turbine test rigs.

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